Human-centered approach for the design of collaborative robotics workstation

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Abstract. Collaborative robotics solutions, where human workers and robots share their skills, are emerging in the industrial context. In order to achieve an appropriate level of Human-Robot Collaboration (HRC), the workstations' design have to be human-centred and adaptive to the workers characteristics/limitations, considering ergonomic crietria. The current study corresponds to the first phase of a research project which intends to apply HRC to minimize the musculoskeletal risk associated with a manual assembly task (in an industrial context of a furniture manufacturer). Regarding this objective, a new workstation was designed and an ergonomic approach was developed to assess the main risk factors, as well as to optimize the future task allocation between human workers and robots. A questionnaire including questions about working conditions and musculoskeletal symptomology was applied to a selected group of 8 workers. Rappid Upper Limb Assessment and Strain Index were applied (across 38 postures) to assess musculoskeletal risk related to the assembly tasks. The results demonstrated that the design and the task allocation for work systems with HRC must be oriented by an ergonomic approach (as developed in the current study). This approach allowed the identification of workers' complaints and risk factors that can be mitigated with the future implementation of HRC.

Keywords: Adaptive human-centered design, Ergonomics, HRC.

1 Introduction

In the emerging context of Industry 4.0, the companies have been looking for several technological solutions and process automation. In the manufacturing industry, human factors must be a focal point when designing these new work systems [1]. Supporting this statement, the European Factories of the Future Research Association (EFFRA) Roadmap 2020 defines as a prerequisite the human-centricity for the factories of the future, foreseeing the development of human competences in synergy with technological progress [2]. This human-centered design can support the increase of flexibility, agility, and competitiveness in the face of new social challenges [3]. Pacaux-Lemoine et al. [4] argue that even existing a lack of research about this topic, an emergent group of researchers, especially in Ergonomics & Human Factors (E&HF), has been focused on the domain of industrial engineering to explore more human-centered manufacturing control system designs.

In the manufacturing companies, the technological revolution of the last decade increased the implementation of robotic solutions, where traditional robots play a major role mainly in handling, welding and joining tasks [5]. In this field, the robotics is often viewed as a tool that can potentially enhance companies' competitiveness [6]. Lindström & Winroth [7] highlight that, in the manufacturing context, these novel systems can be designed according to different approaches, such as:

(i) Techno-centered approach, focusing on the optimization of the shop floor production, with inflexible work systems based on automatic and predefined operations;

(ii) Human-centered approach, allocating to the human workers the tasks more suitable to them, combining the automation/robotics to help the human work.

In the industry of the future, despite the intention for technological solutions development, it is not aimed to have fully robotized production processes – the human component is still extremely relevant. In the manufacturing contexts, optimizing task allocation would increase the systems' robustness due to complementarities of technology efficiency with the flexibility of humans [7]. The E&HF scientific area must support these tasks' allocation and the design and implementation of these new work systems. Human workers will be integrated into the industrial systems in order to properly explore their skills and, at the same time, ensuring their wellbeing and safety. Therefore, the industrial implementation of technologies, such as Human-Robot Collaboration (HRC), must be human-centered.

HRC is an appealing prospect to the industry in general due to the high degree of adaptability and flexibility [8]. Of those, flexible robotic solutions with intuitive and natural human-machine interfaces and capable of intelligent decision making – COBOTs – are key players. COBOTs or Collaborative Robots are a sub-type of robots specially tailored to work in close proximity to humans or other robots. Although the concept is not new, recent breakthroughs in robotic sensorization and in the integration of safety-rated technology with industrial robots have permitted the certification of the first systems that can operate alongside humans [9]. In times when the topic of the human labor replacement by robots generates so much controversy [10], the design of new workstations where robots collaborate with the operator is an encouraging vision.

In this domain, the human-centered design of the workstation with HRC must be adaptive, including various criteria, such as age, disability, and inexperience-related restrictions of the workers in order to increase their working capabilities [3].

The current study corresponds to the first phase of a research project which intends to apply collaborative robotics in order to minimize the musculoskeletal risk associated with a manual assembly task (in an industrial context of a furniture manufacturer). Regarding this objective of the mentioned project, an ergonomic approach was developed to assess the main risk factors and to optimize the future task allocation between human workers and robots. Therefore, the current study is focused on the ergonomic approach for the design of a new workstation with a collaborative robot.

2 Methodology

The industrial section is composed of 60 female workers, who perform continuously manual assembly tasks to produce MDF frames. However, in a previous phase of the research project, it was verified that these workers presented different musculoskeletal problems related to their exposure to different risk factors, such as repetitive movements, hand-force application, and awkward postures. Based on this evidence, the development of the project allows the creation of a new workstation in order to accommodate the workers with musculoskeletal complaints. In this workstation (named pre-assembly), the subproduct consists in MDF stripes and blocks glued, which will be transformed in a subsequent workstation of final assembly to form final frames, as represented in Figure 1.

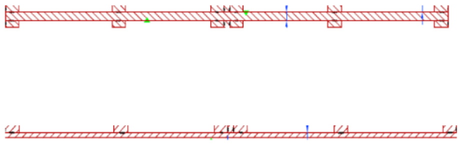

Fig. 1. Example of a subproduct of the workstation studied (MDF preforms).

The tasks developed are as follows: (1) Reach for the stripes from pallet 1 and place them in the assembly workbench; (2) Pick the blocks from a box; (3) Reach for the glue gun; (4) Apply glue to the blocks; (5) Put down the glue gun; (6) Glue the blocks to the stripes; (7) Dislodge, rotate and place back the stripes to the workbench; (8) Dislodge the stripes; (9) Transfer the stripes to the pallet 2; (10) Resupply the glue gun.
A group of 8 workers was selected to test this new workstation (Figures 2 and 3). This selection was based on the prevalence of musculoskeletal complaints and was applied by the company´s practitioners. Foreseeing the implementation of a collaborative robot to support the assembly work, an ergonomic assessment was developed.
Primarily, a questionnaire was applied to the workers ($n = 8$). Demographic data, workers' perceptions about the working conditions and musculoskeletal symptomology were collected. The part of the questionnaire regarding the prevalence of musculoskeletal complaints was based on the Portuguese version of the Nordic Musculoskeletal Questionnaire (NMQ) [11]. The NMQ allows the identification of self-reported musculoskeletal symptomatology across 9 body regions (neck, shoulders, elbows, wrist, thoracic, lumbar, thighs/hips, knees, ankles/feet). For each of the body regions, the respondents have to indicate if felt pain/discomfort in the last 12 months and in the last 7 days.
Relatively to the working conditions, the questions were based on the Ergonomic Workplace Analysis (EWA) method [12]. These questions were applied in order to achieve a comprehensive assessment of the workstation, across 14 topics (T), namely: (T1) workspace; (T2) general physical activity; (T3) lifting tasks; (T4) work postures and movements; (T5) risk of accident; (T6) work content; (T7) restrictiveness; (T8) workers' communication; (T9) decision-making; (T10) work repetitiveness; (T11) level of required attention; (T12) lighting; (T13) thermal conditions; and (T14) noise. These topics were assessed by a scale with a four-level rating scale: "very bad" (- -);

“bad” (-); “good” (+); “very good” (+ +) [12]. Questions related to the physical exertion self-reported for the assembly tasks were evaluated by Category Ratio-10 (CR-10) [13].

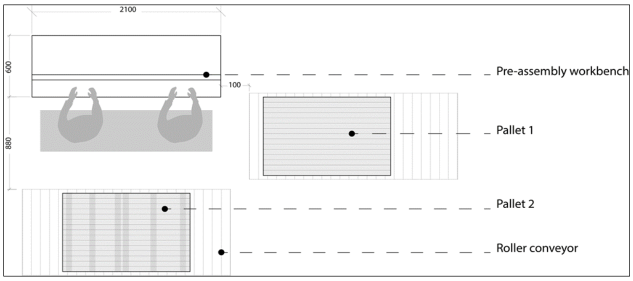

Fig. 2. Workstation organization (dimensions in mm).

Fig. 3. Examples of adopted postures.

Posteriorly, the ergonomic assessment included the WMSD risk assessment by Rapid Upper Limb Assessment (RULA) [14], and Strain Index (SI) [15]. RULA method was used for assessing WMSD risk for the upper limbs, considering also the neck, trunk and lower extremities position during work activity. Its application involves the assessment of the postures adopted by the worker during task performance, as well as the forces exerted, the repetitiveness of movements and external loads (such as handling loads) [14]. The SI evaluates the musculoskeletal risk for the distal upper extremity disorders, considering 6 variables: intensity of exertion, duration of exertion per cycle, efforts per minute, hand/wrist posture, speed of exertion, and duration of task per day [15].
The software IBM® SPSS® Statistics, version 26.0, was applied to analyze the results. In this domain, a descriptive analysis of the data was developed, calculating mean values of quantitative variables (e.g. age). The workers' assessment in EWA and the prevalence of the musculoskeletal symptoms were expressed in a relative percentage, evidencing the values distribution. The McNemar test – a specific test of the Chi-square for paired samples – was used in order to test the concordance between the musculoskeletal pain prevalence between the two periods considered in the NMQ (last 12 months and last 7 days). Finally, the ratings of exertion perceived by workers and the final ratings of RULA and SI were expressed using the mean as a measure of central tendency. The different ratings of RULA and SI were obtained by the analyst considering different postures for each task (a total of 3 to 6 postures most frequent for each task depending on the postural variability).

3 Results

3.1. Participants characterization and questionnaire results

The sample of 8 female workers who tested the workstation present a mean age equal to 49.9 (± 7.7) years old and they have a mean of work experience of 10.9 (± 0.4) years at the assembly section (Table 1). All of these workers are right-handed and reported one or more musculoskeletal disorders, namely: carpal tunnel syndrome (n = 5), disc herniation (n = 1), tendinitis (n = 2).

Relatively to the NMQ results (Figure 4) the McNemar test proved that exists a perfect concordance (p = 1.000) between the workers' perceptions for the last 12 months and the last 7 days across the body regions considered. Therefore, the NMQ results presented in Figure 4 are related to the prevalence of musculoskeletal discomfort/pain along the last 12 months (the more extended period of time). In addition, EWA results based on the workers' perceptions are presented in Figure 5.

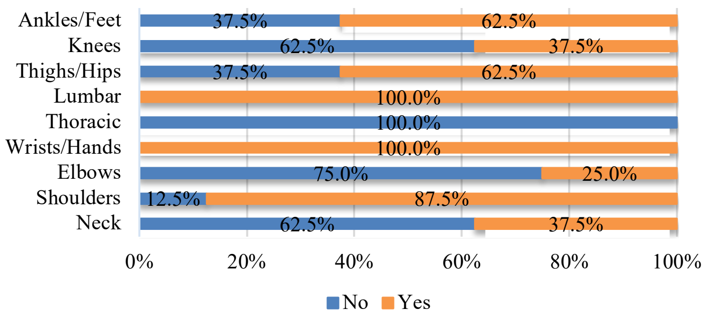

Fig. 4. Prevalence of musculoskeletal pain/discomfort across the different body regions.

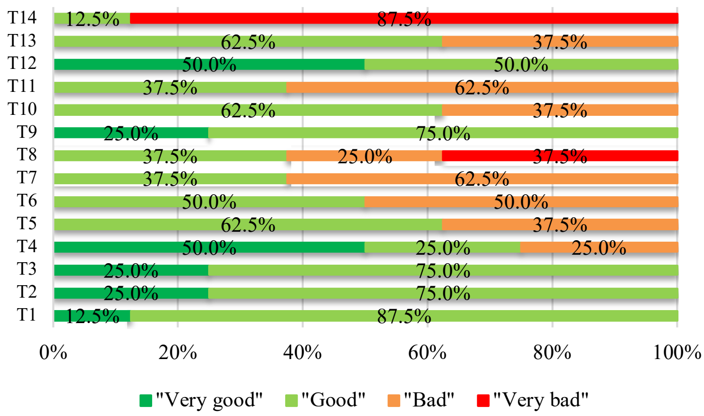

Fig. 5. EWA results – workers' assessment.

3.3. Results of exertion perceived and WMSD assessment

The workers' perceived exertion along to the 10 assembly tasks is presented in Table 1. The final mean ratings of the RULA and SI assessments are also presented. Figure 5 presents examples of postures adopted during the tasks with higher risk levels (according to the RULA and SI assessments).

	CR-10 (8 workers)	RULA (analyst assessment)		SI (analyst assessment)	
Task	Rating mean (SD)	Rating mean (SD)	Risk Level	Rating mean (SD)	Risk Level
Task 1	2.6 (0.5)	3.2 (0.4)	II	0.3 (0.1)	I
Task 2	2.1 (1.0)	3.6 (0.9)	II	1.5 (0.6)	I
Task 3	2.6 (1.4)	3.0 (n.a.)	II	1.2 (0.5)	I
Task 4	**4.1** (1.6)	3.0 (n.a.)	II	**5.1** (1.5)	III
Task 5	2.6 (1.4)	3.0 (n.a.)	II	1.2 (0.5)	I
Task 6	2.0 (0.9)	**4.4** (0.5)	II	1.0 (0.7)	I
Task 7	3.3 (0.7)	3.0 (n.a.)	II	0.6 (n.a.)	I
Task 8	2.1 (1.2)	3.2 (0.4)	II	0.1 (n.a.)	I
Task 9	1.8 (0.9)	**4.4** (1.3)	II	0.1 (n.a.)	I
Task 10	1.0 (n.a.)	3.0 (n.a.)	II	0.2 (0.1)	I

Table 1. Summary of the CR-10, RULA and SI results.
Legend: n.a. – not applicable.

4 Discussion

The NMQ results (Figure 4) demonstrated that the body regions with a higher incidence of musculoskeletal problems are the lumbar region and the wrists/hands. The awkward postures and repetition of actions are important risk factors for these body regions and these factors are present in the workstation studied. Additionally, according to the workers' perceptions (Figure 5) the factors more critical are the following: noise (T14, with a more negative distribution of the answers); workers' communication (T8); restrictiveness (T7); and level of required attention (T11). Therefore, in this redesigned-workstation the workers continue presenting musculoskeletal complaints, indicating that this workstation could/should be improved.

The main results of the RULA assessment indicate that Tasks 6 and 9 imply a higher musculoskeletal risk when compared with the other tasks. However, in Task 6 the upper limbs are more affected because of the posture adopted during the gluing of the blocks to the stripes. As evidenced in Figure 3, the shape and size of the blocks handled lead to the frequent ulnar deviation and extension of the hand-wrist system. In Task 9, during the stripes transfer to the pallet, the neck and trunk are more affected due to the neck extension, to the flexion and inclination of the trunk, and to the bodyweight which is unevenly balanced. These findings demonstrated that the workstation should be redesigned for this task. Therefore, the implementation of a lifting table should be considered as well as the elimination of the lateral roller conveyor. The actual design significantly compromises the workers' posture during the subproducts transferring to the pallet.

The fact that the majority of the workers present musculoskeletal disorders affecting the wrists (carpal tunnel syndrome) increases the concern about the risk assessment, which also includes methods more focused on the hand-wrist system, such as SI. The SI results pointed out to a higher musculoskeletal risk associated with Task 4 (apply glue), mainly due to the intensity exertion perceived by the 8 workers. However, according to the RULA, the higher rating was assigned to Task 6 (fix blocks), mainly for the upper body. These differences between methods conclusions are related to the fact of variables measured being different. In addition to biomechanically unfavorable postures for the hand-wrist system, this task involves glue gun handling, increasing the musculoskeletal risk mainly due to the intensity of exertion associated (as evidenced by the mean values of CR-10 ratings reported by the workers).

Based on the current study, the implementation of a COBOT in this workstation could improve the ergonomic conditions. For instance, this technology could support the assembly tasks performed, eliminating the most critical tasks (such as Task 4 – apply glue). The contributions of the E&HF scientific area must be considered in order to implement adaptive human-centered work systems, where the robotics allows a dynamic and seamless transition of tasks' allocation between human workers and COBOTs, providing inclusiveness and job satisfaction, simultaneously with the production goals achievement [3]. In addition, the workers' perception of load and health disorders are important indicators of the workload [12, 13]. Based on this assumption, the workers' opinions must be included along with future work.

5 Conclusions

For the factories of the future, the adaptive human-centered design can potentiate the implementation of innovative technologies, such as the COBOTs. This implementation must consider inputs for E&HF in order to optimize the task allocation in work systems with HRC. The results showed that in this specific workstation the introduction of a COBOT could be oriented in order to eliminate the most critical task and to accommodate the workers with musculoskeletal complaints. Therefore, the current ergonomic assessment supports the future work associated with the COBOT implementation.

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References

1. Leso, V., Fontana, L., Iavicoli, I.: The occupational health and safety dimension of Industry 4.0. La Medicina Del Lavoro 109(5), 327-338 (2018).
2. EFFRA – European Factories of the Future Research Association (2016). Factories 4.0 and Beyond, https://www.effra.eu/sites/default/files/factories40_beyond_v31_public.pdf, last accessed 2019/08/05.
3. Romero, D., Noran, O., Stahre, J., Bernus, P., Fast-Berglund, Å.: Towards a Human-Centred reference architecture for next generation balanced automation systems: Human-automation symbiosis. In: Umeda S., Nakano M., Mizuyama H., Hibino H., Kiritsis D., von Cieminski G. (eds). Advances in Production Management Systems: Innovative Production Management Towards Sustainable Growth, Vol. 460, pp. 556-566, Springer (2015).
4. Pacaux-Lemoine, M.P., Trentesaux, D., Rey, G.Z., Millot, P.: Designing intelligent manufacturing systems through Human-Machine Cooperation principles: A human-centered approach. Computers & Industrial Enginnering 111, 581-595 (2017).
5. Heydaryan, S., Bedolla, J.S., Belingardi, G.: Safety Design and Development of a Human-Robot Collaboration Assembly Process in the Automotive Industry. Applied Sciences 8, 2-22 (2018).
6. Salim, R., Johansson, J.: Automation decisions in investment projects: A study in Swe-dish wood products industry. Procedia Manufacturing 25, 255-262 (2018).
7. Lindström, V., Winroth, M.: Aligning manufacturing strategy and levels of automation: A case study. Journal of Engineering and Technology Management: 27, 148-159 (2010).
8. Lu, Y.: Industry 4.0: A Survey on Technologies, Applications and Open Research Issues. Journal of Industrial Information Integration 6:1–10 (2017).
9. Bischoff, Rainer, Johannes Kurth, Günter Schreiber, Ralf Koeppe, Alin Albu-Schäffer, Alexander Beyer, Oliver Eiberger, Sami Haddadin, Andreas Stemmer, Gerhard Grunwald, and Gerhard Hirzinger: The KUKA-DLR Lightweight Robot Arm - A New Reference Platform for Robotics Research and Manufacturing. In: Joint 41st International Symposium on Robotics and 6th German Conference on Robotics 2010, ISR/ROBOTIK 2010, Vol. 2, pp. 741–48 (2010).
10. Weiss, A., A. Huber, J. Minichberger, and M. Ikeda: First Application of Robot Teaching in an Existing Industry 4.0 Environment: Does It Really Work?. Societies 6(3):20 (2016).
11. Mesquita, C., Ribeiro, J., Moreira, P.: Portuguese version of the standardized Nordic musculoskeletal questionnaire: Cross cultural and reliability. Journal of Public Health 18(5), 461-466 (2010).
12. Ahonen M., Launis M., Kuorinka T.: Ergonomic Workplace Analysis. Helsinki: Finnish Institute of Occupational Health. Ergonomics Section (1989).
13. Borg G.: Psychophysical scaling with applications in physical work and the perception of exertion. Scandinavian Journal Work Environmental Health 16(suppl 1), 55-8 (1990).
14. McAtamney, L., Corlett, E.: RULA: a survey method for the investigation of work-related upper limb disorders. Applied Ergonomics 24(2), 91-99 (1990).
15. Moore, J.S., Garg, A.: The strain index: A proposed method to analyze jobs for risk of distal upper extremity disorders. American Industrial Hygiene Association Journal 56(5), 443-458 (1995).